

Design of a Multi-Week Sound and Motion Recording and Telemetry (SMRT) Tag for Behavioral Studies on Whales

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LONG-TERM GOALS

This project will lead to the development of new tag technology to study the behavioral effects of sound on wild marine mammals over extended time intervals. This technology will enable fine-scale studies of sound exposure and responses under authentic conditions and will provide data needed to assess the biological significance of responses.

OBJECTIVES

The project requires the integration of technologies from three tag developers. As a first step towards the development of a sound and motion telemetry tag, the current project aims to:

1. Assess the feasibility of combining in situ acoustic and motion processing with ARGOS telemetry, Fastloc GPS, and a trans-dermal pin attachment to produce a medium-term cetacean tag.
2. Establish an intellectual property agreement between the partner organizations to enable sharing of the technologies required by the project.
3. Develop a detailed specification for the medium-term tag and perform preliminary engineering on critical mechanical and electronic sub-systems in the tag to minimize risk areas in the design.
4. Begin publication of the data processing methods that will be used in the tag.

APPROACH

Studies of the impact of human-sourced sound on marine mammals have been greatly aided by multi-sensor tags such as the DTAG that simultaneously sample the sounds experienced by animals and their fine-scale behavior. Unfortunately the recording time of these tags is limited to a few days and there is currently no tag technology available for monitoring behavioral responses to longer sound exposures such as Navy sonar exercises. To sample before, during, and after these exercises, a tag duration of 2-3 weeks may be required, a ten-fold increase over current sound recording tags. Designing a tag for such long durations entails major challenges. It may be expensive or infeasible to recover tags that are attached to whales for several weeks necessitating that essential information be transmitted via low data rate satellite telemetry. Thus, a high level of data selection and compression must be performed by the tag. Another major constraint on a multi-week tag is its size. A relatively small, hydrodynamic tag is required both to ensure reliable attachment for the required time, and to minimize impact of the tag on the host animal. As a consequence the battery volume, and therefore energy, is strictly limited necessitating extremely efficient electronic circuits.

In previous ONR-funded work at St Andrews, we evaluated the possibility of a medium-term tag that computes highly compressed behavior and exposure metrics in real-time while attached to an animal. This project led to the concept of a tag that would collect data over an interval of several weeks and then release from the animal to float at the surface where it would transmit the stored summary data via Argos satellite radio. The tag would also contain a partial data archive in case it was possible to retrieve it. In support of this concept, we developed a suite of robust in situ processing algorithms for sound and motion data. In a parallel project Dr. Andrews at the Alaska SeaLife Center teamed with Wildlife Computers to develop a medium-term attachment method for cetaceans involving a set of short barbed darts that anchor in the dermis. In the current project, we will combine these data processing and animal attachment methods with existing Fastloc GPS, Argos telemetry and marine tag manufacture methods from Wildlife Computers to produce a highly integrated Sound and Motion Recording and Telemetry (SMRT) tag. The complete tag development is expected to require three years encompassing design and preliminary engineering (the current project), followed by two years of prototype development and field evaluation.

The development project is not only challenging from an engineering perspective but also requires the collaboration of tag manufacturers that otherwise work independently and, to some extent, compete. The project therefore requires legal and engineering frameworks to enable collaboration of these groups. Given the risk that the groups may fail to reach an agreement on technology sharing or may conclude that, on evaluation, the tag is not currently feasible, a single exploratory year of funding was requested. The goals in this initial year were to examine the capabilities and technologies needed in the tag, and to then develop a detailed specification. A go/no-go point was identified in the proposal allowing for work to end if agreement was not reached on how to develop the tag. Following this decision, a second phase of work was proposed involving detailed analysis of two elements of the tag judged as being the most critical from an engineering perspective. In this phase, work at St. Andrews would focus on the design of a prototype sound and motion processing module and in continuing the implementation and publication of the in situ data processing methods developed in the previous ONR project. Work under a companion proposal at Wildlife Computers and at the Alaska SeaLife Center would focus on the mechanical design and materials selection for the tag. Successful development of these components will greatly reduce the risks in producing a prototype tag for field evaluation in the following year.

WORK COMPLETED

The initial design review meeting took place on May 11th-13th at Wildlife Computers (WC) in Redmond, WA. P.I.s Johnson, Lindstrom and Andrews attended along with mechanical, electrical and software engineers from WC. Prior to the meeting, a non-disclosure agreement was signed between St. Andrews and WC allowing discussions of proprietary technology. The initial goal of the meeting was to establish the feasibility of the SMRT tag project from an engineering and commercial viewpoint. As the design will incorporate elements developed independently by the project partners, our concern was to establish how readily these components could be combined and to reach an agreement on how we would work with these proprietary technologies. Accordingly, on the first day we formed a preliminary specification for the tag and discussed intellectual property issues. Agreement was reached regarding the feasibility of producing a SMRT tag. However, it was also agreed, based on field experience, that the extremely low throughput of Argos will constrain the data telemetry function of the tag irrespective of the efficiency of on-board data summary algorithms. The high rate of non-delivered data (up to 95%) will inevitably result in sparse retrieved data sets with lengthy outages during which little can be gleaned about the behaviour of the animal. This led us to place an increased emphasis on the archival capability of the tag and to consider the primary function of telemetry, at least initially, as an aid for recovering the tag (e.g., by sending GPS positions) and for verifying that a tag has sufficient data to justify the effort of recovery. It was agreed therefore that our initial R&D efforts should focus on an archival tag which floats after release and transmits positional information as well as synopses of the data collected. The tag would have computational capacity for the later addition of more sophisticated data processing for telemetry, the design of which would be informed by the actual data recovery rates from initial prototype tags. Compared to existing tags, the proposed tag provides a unique combination of capabilities: multi-week sound recording, Fastloc GPS positioning, reliable medium-term cetacean attachment and data synopsis telemetry, which will make it immediately useful for behavioural response studies. This evaluation was shared with the program manager in a phone conference during the meeting and agreement was reached to continue with the second phase of this one year feasibility project, i.e., to produce a detailed specification for the tag and to begin engineering work on the high risk sub-systems.

The remainder of the 3-day meeting was devoted to in-depth analyses of the mechanical, electronic, and software issues in marrying the technologies in the tag. This resulted in a set of detailed specifications that summarize the capabilities needed in the tag. We also discussed how to move forward on sub-systems of the design so as to reduce risk at the prototype development phase. As anticipated, agreement was reached that the main risk areas lay in (i) the integrated mechanical design of the tag, and (ii) the sound and motion module which must consume very little power to enable a compact implementation. Accordingly, detailed specifications were developed during the meeting and in follow-on work for these elements of the tag.

Mechanical design

A set of key constraints informing the mechanical design of the tag were identified in the meeting. The tag must be suitable for pole or ballistic deployment and must attach using a set of 3-4 trans-dermal barbs. The tag body must have a compliant connection to the barbs to reduce impact on the sensors in the tag. The body should also be hydrodynamically-shaped when attached to the animal. As there may be relatively little control of how the tag is placed on the animal, the Fastloc GPS and Argos antennas, and the hydrophone must be located so that these are protected during deployment and are positioned appropriately in most probable attachment orientations. After releasing from the animal, the tag must float at the sea surface and orient so as to position the Argos antenna and a second (non-Fastloc) GPS

antenna out of the water. Finally, the tag must withstand immersion to at least 2000 m depth and be cast in appropriate materials to allow sensing of pressure, sound, animal movement and GPS radio signals. As the eventual release of barbs from an animal is inevitable, a release mechanism, although considered desirable, was excluded from the initial design for simplicity.

The tightly-integrated tag design required to meet these constraints will ultimately result from a feedback process between the electronic and mechanical designs. As a first step, mechanical engineer S. Walton at Wildlife Computers produced a 3 dimensional design for the tag which will be discussed in the following section. This design requires a range of encapsulation materials including compliant, rigid, and low-density materials. Wildlife Computers often combines materials within a tag and has found that adhesion between materials is critical for adequate structural performance. Of particular concern in this design is the combination of rigid and elastomeric materials needed to protect electronics and yet allow pressure sensing at the hydrophone. A range of castable polyurethanes were evaluated in terms of their bond strength to epoxy and their water absorption. Test specimens of 0.5" diameter were prepared for each elastomer comprising a layer of the elastomeric material followed by a layer of epoxy. The casting method was designed to emulate Wildlife Computers' current manufacturing methods and capabilities. A flexure test of the composite was used to test adhesion between materials. The samples were also exposed to cleavage stress by bending to 90°. In parallel, multi-month water absorption tests of the elastomers were begun using a 40°C salt water chamber kept at 60psi. A short-list of suitable materials have been identified as a result of these tests.

Sound and Motion Module

The kernel of the SMRT tag is a miniature, low power module to acquire, process and archive data from sound and motion sensors. This module must take less than 20% of the power of the current DTAG for the SMRT tag to be small enough for multi-week deployment on species of interest, requiring a complete re-design of the DTAG sound acquisition circuits. Prior to the initial design meeting, P.I. Johnson produced trial circuits of a novel low-power hydrophone preamplifier and sound acquisition circuit to verify that the target power consumption was feasible. Work on the sound and motion module after the meeting was impacted by the late arrival of funds from ONR (late July at University of St. Andrews and mid-August at Wildlife Computers). Although significant work was carried out prior to these dates, largely covered by a pre-spend authorisation, uncertainty about funds led us to postpone circuit board fabrication, a fixed expense of \$6000. To offset this delay, work was accelerated on a closely-related project funded by the European Science Foundation under a Marie-Curie grant to Johnson. This project involved the development of a long-term sound recording tag for seals, called the 'D4'. The D4 board is a close approximation to the SMRT module in terms of circuit design, fabrication technology, and software. Early fabrication of this board therefore enabled realistic performance predictions and design errors to be established before committing to the SMRT board design as well as providing a development platform for the SMRT embedded software. The D4 board was sent to fabrication in June and prototype boards were received in August. These have now been fully evaluated with results reported in the following section. Some small design errors were found on the board but performance was very close to predictions. Leveraging this design, P.I. Johnson is now completing the layout of the SMRT sound and motion board. Fabrication will begin in October and boards will be available for testing in December. St Andrews will request a no-cost extension to continue testing and software implementation on this board past the nominal project end date.

Processing algorithms

A parallel objective of the project was to continue the implementation of on-board processing algorithms for the SMRT tag and to prepare a publication describing these methods. The focus was on

methods for summarizing sound data given that this represents 99% of the data volume collected by the tag. Ambient noise levels experienced by the tag will likely form part of the synopsis information sent via Argos and used to assess the value of recovering a tag. Accordingly, work has continued in testing and implementing methods for quantifying ambient noise. In order to assess the robustness of these methods, we compared their performance using data from three species of deep-diving marine mammals (Blainville's beaked whales, short-finned pilot whales and sperm whales) taken from the DTAG data archive. The results of these analyses are reviewed in the next section and a manuscript describing the work is currently being prepared for publication.

Follow-on work

The late arrival of funding also led us to change the date of the second project meeting which was initially planned for August. The objectives of the meeting were to assess progress and generate a proposal to fund the next work phase. These objectives have been met with a telephone conference and follow-on funding applications are currently being prepared for ONR and Living Marine Resources. We therefore propose to postpone the second project meeting until the sound and motion circuit board is ready for testing with the Wildlife Computers controller board. The meeting will be used both to complete funding applications and to begin system integration.

RESULTS

Physical design

The physical design of the SMRT tag is dominated by two considerations: the tag must be relatively small so as to add little drag to the host animal and it must float upright when released. To achieve this, dense components such as batteries must be minimized and located at the opposite end of the tag from the antennas leading to the preliminary design shown in Fig. 1. The maximum battery weight that could reasonably be incorporated in this tag is about 50 g, roughly equivalent to 2 x AA batteries giving a total power capacity of 16 Whr. Combined with the electronics and sensors, a total tag volume of 290 cm³ with a dry weight of 220 g is predicted (Fig. 2), comparable to the DTAG-3.

To assess the adequacy of this battery capacity, we examined consumption by sub-system and functional mode. The tag switches between two modes during a deployment: it first collects data for 2-3 weeks while attached to an animal and then floats at the surface in a recovery mode for several more weeks. While floating, an Argos transmission will be made every minute and a GPS position will be taken every 30 mins but the remainder of the tag will be shutdown. Assuming a 3 week recovery time, about 8 Whr will be required, close to the capacity of an AA lithium cell. In the data collection mode, the tag will sample sound and motion sensors continuously, archiving and processing these data. The tag will also make about 100 Fastloc GPS acquisitions and 200 Argos transmissions per day. Over 14 days, the GPS and Argos will consume 1 Whr leaving 7 Whr for the sound and motion module and the implications of this are discussed below. This power allocation scheme allows for some 30,000 Argos transmissions with 30 bytes each for a total data output of almost 1 MByte. But because Argos satellites are not continuously available, only 5-10% of these transmissions will be received requiring that critical data is sent multiple times. Based on experience with other Argos tags, we estimate that only 500-1000 unique messages will be delivered and correctly decoded in 3 weeks for a total data throughput of about 15-30 kBytes. For this reason, we see the primary role of Argos telemetry in the first generation SMRT tags to be a recovery aid and to provide an indication of the data held by the device rather than to transmit significant behavioural and noise exposure data.

From a materials perspective, the main concern in the design of Fig. 1 is the bond between the elastomer around the hydrophone and the epoxy tag body. Of six urethane materials evaluated, two were found to have adequate bond strength and process compatibility. In bend testing, some elastic deformation was noted in the urethane close to the transition with the epoxy and this will be considered when designing the interface between the hydrophone and tag body. One of the urethanes was used to encapsulate a hydrophone for pressure testing. The cast hydrophone survived pressure equivalent to a depth of 2000 m without damage.

Sound and motion module

The D4 board used here as a proxy for the SMRT sound and motion module (Fig. 3) contains the same sensor systems, support circuits and digital signal processor and so provides a realistic test platform for the SMRT module. The D4 board was tested running at the target audio sampling rate of 192 kHz while compressing and archiving data. The measured current consumption was 5 mA giving a power consumption over 14 days of 6 Whr, significantly less than the 7 Whr allocated to this sub-system. Despite the low current consumption, the acoustic performance of the D4 board is excellent with a high frequency noise floor of 3 nV/ $\sqrt{\text{Hz}}$ and a flat frequency response to 70 kHz, sufficient to sample sounds from beaked whales and most delphinids. The D4 board is about 25% larger than the target size for the sound and motion module but contains a number of circuits which are not needed on this board. Thus both the power and dimensional constraints are attainable and work is continuing to produce prototype boards in the configuration required for the SMRT tag.

Ambient noise monitoring

Work is advancing on a paper describing an in situ processing method, developed in a previous ONR project, for estimating the ambient noise from tag sound samples. In this paper we show that a modified form of spectral analysis reduces errors from sounds generated by the tagged animal (Fig. 4) while a motion metric computed from an on-board accelerometer enables detection of epochs with low flow noise. To validate these methods, we selected DTAG data from three deep-diving species in which tags detached from animals during dives (Fig. 5). These data indicate that while frequencies above 10 kHz are minimally affected by flow noise, low frequency measurements are only possible when the animal is relatively still restricting the temporal resolution. Within this limitation, the ambient noise method is simple and robust and so is well-suited to implementation in the SMRT tag where it will provide a compact indication of data quality compatible with the limited Argos bandwidth.

The success of the work carried out so far indicates that it is feasible to continue the development of the SMRT tag albeit with an initial focus more on an archival device with limited data telemetry. The next step will be to produce a prototype tag for testing incorporating the components described here. In parallel, we will need to develop testing and validation methods for both the hardware and data synopsis algorithms. Depending on funding timelines, a realistic goal will be to produce field-ready tags within the next 18 months.

IMPACT/APPLICATIONS

National Security

Concern about potential impacts on acoustically-sensitive cetaceans has constrained some Navy activities. The project is developing critical tag technology needed to study the effects of sound on cetaceans over extended intervals and under authentic conditions. This information will strengthen models of population-level consequences of sound and will aid in Navy planning.

Economic Development

Economic development brings increasing noise to the ocean from ship traffic, construction, and mineral exploration. An improved understanding of how noise impacts marine mammals, aided by the technology developed here, will help to make economic growth sustainable.

Quality of Life

The measurement devices to be developed as the long-term goal of the project will contribute information about the sensitivity of cetaceans to human activities. This information will help improve methods for predicting and mitigating the impacts of these activities leading to more effective management of an important natural resource.

Science Education and Communication

Results from the project will be presented at conferences and in the scientific literature. Software and hardware products of the project will be commercially available to the research community.

RELATED PROJECTS

A micro sound recording tag for bats (2014-2015): In this cooperative project between University of St Andrews and Aarhus University in Denmark, funded by the Danish Science Foundation, we developed a miniature sound recording tag suitable for use on bats. This 2 g tag required a completely new electronic design approach to achieve the size and power consumption constraints. The sound and motion module in the current project is derived from this design.

PUBLICATIONS

Johnson M, "On-Animal measurement of ambient noise". [in prep]

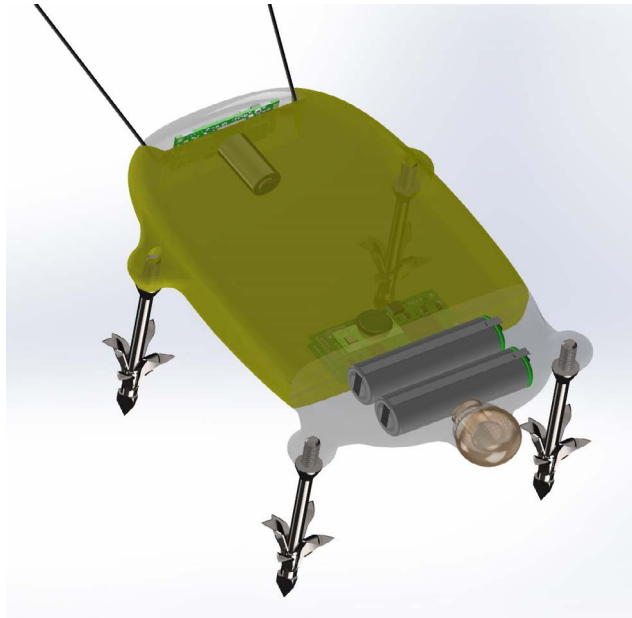


Figure 1: Preliminary mechanical drawing of the SMRT tag showing the 4 attachment barbs, the epoxy casting (grey) and the floatation material (green). A spherical piezo-ceramic hydrophone is located at the front of the tag while antennas for Argos and GPS are positioned at the rear. The batteries, circuit boards and floatation material are arranged so that the tag floats stably with the antennas out of the water after releasing from an animal.

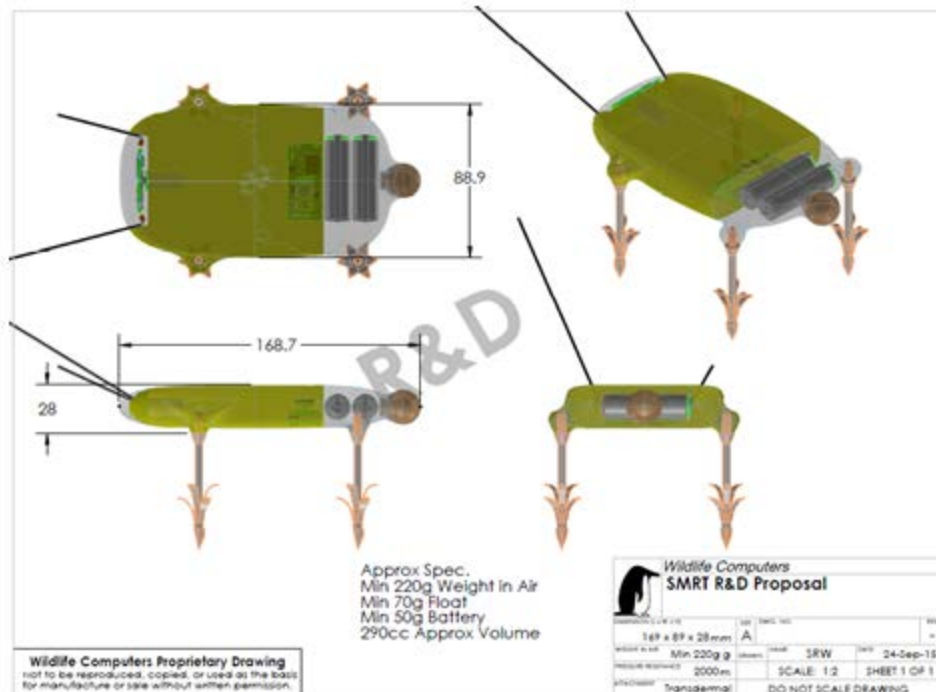


Figure 2: Mechanical drawing of the tag showing approximate dimensions, weight and volume.

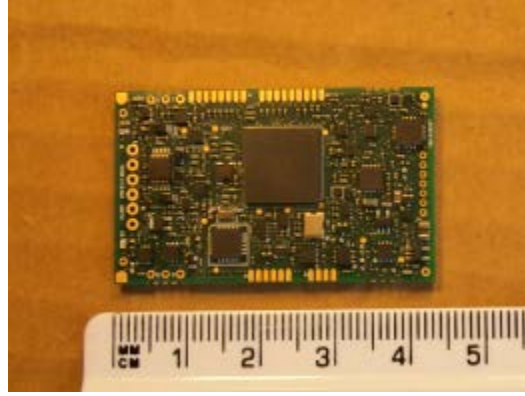


Figure 3: Photograph of the D4 single board sound recording tag on which the sound and motion module for the SMRT tag is based. This board, designed for a long-term DTAG, contains identical sound acquisition and processing circuits as in the SMRT board and so has been used to verify performance, measure power consumption and begin software development.

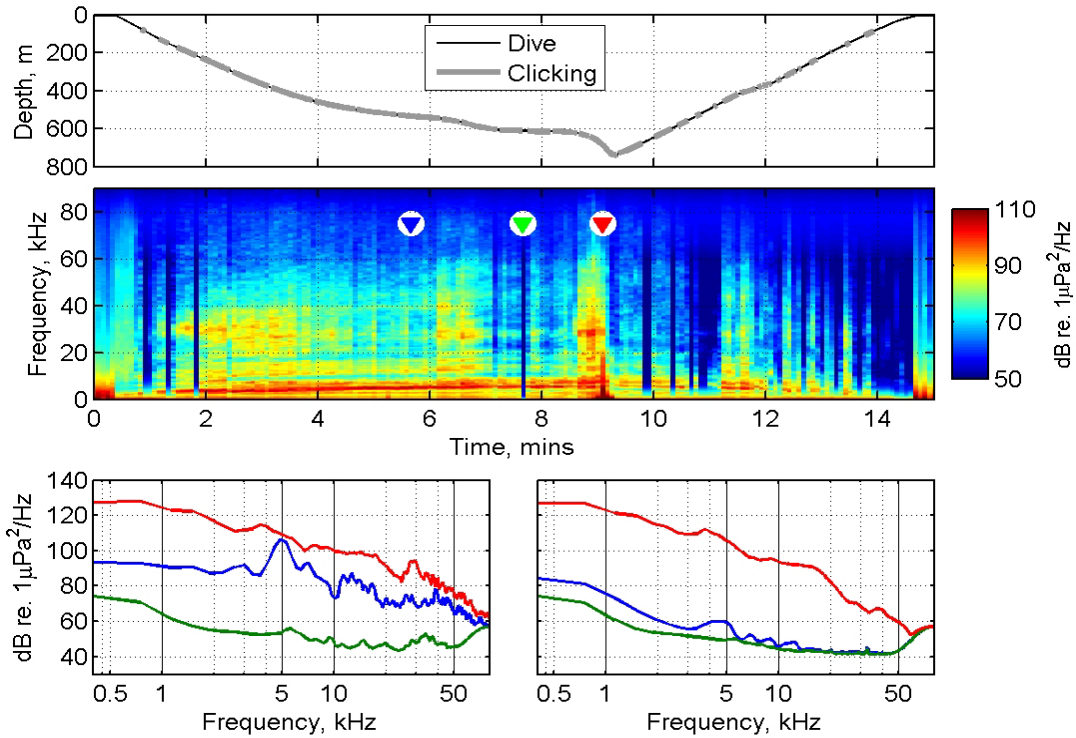


Figure 4: Impact of animal movement and sound production on apparent ambient noise level as measured by a sound recording tag. Here consecutive 5 second spectral averages of the sound recorded by a tag on a short-finned pilot whale during a deep foraging dive are shown. Occasional vertical blue bands indicate when self-noise is low enough to measure the actual ambient noise level. The lower panels shows the spectral level computed in two ways at the times indicated by arrows in the middle plot. The standard spectral average in the left panel is strongly affected by animal-generated sounds (blue line) and flow noise (red line) leading to noise estimates which are 20-50 dB above the ambient noise (green line). Animal-generated sounds (blue line) but not flow noise (red line) are removed effectively by using a trimmed spectral mean (right hand panel).

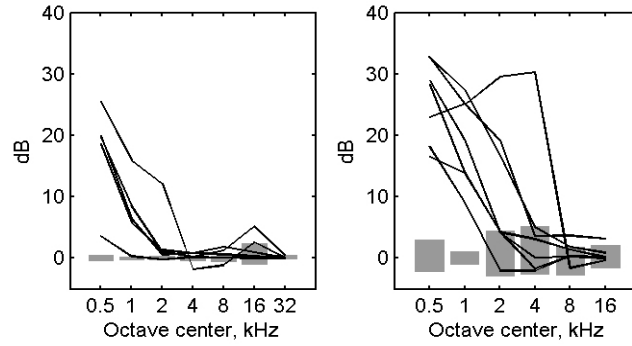


Figure 5: Octave levels recorded from tags on Blainville's beaked whales (left), and short-finned pilot whales (right) shortly before (black lines) and after (grey bars) detachment of the tag in 5 and 7 individuals of each species. The measurements taken when the tag was attached correspond to the 5 s interval with the lowest vectorial dynamic body acceleration (VeDBA) in the minute preceding tag detachment. Trimmed mean octave levels are used to reduce animal-generated sounds. All spectra are referenced to the mean levels recorded in the minute following detachment. The grey bars show the minimum to maximum levels recorded after the tag detached. Above 2 kHz, there is little difference between the on- and off- animal noise levels when VeDBA is low suggesting the use of this motion measure as a quality metric. Similar analysis have also been performed on sperm whales (not shown).